

A Small Satellite Concept for On-Orbit Servicing of Spacecraft

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Abstract. Over the past six years, over two billion dollars worth of commercial, civil, and military satellites have been written-off as a result of launch and on-orbit failures. Many of these failures would be relatively straightforward to repair on the ground but the equivalent repair in space is thought to be costly and technically difficult. It is proposed that a Smallsat could be ideally suited to perform some of these repairs, for instance, to provide attitude sensing if a sensor has failed. In this scenario, the Smallsat servicer vehicle would remain attached to the client satellite to provide the attitude determination function. Such a Smallsat mission would be far more cost effective than scrapping an otherwise functional large satellite and purchasing its replacement.

The key technical difficulty is that most current satellites are not designed for robotic servicing. Challenges include docking with an uncooperative interface and then closing the control loop between the servicer vehicle, the client satellite, and the ground. This paper provides a definition of the Smallsat servicing system concept. It discusses rendezvous techniques, docking subsystem design, and ground segment operations. Strategies to deal with communication latency are also discussed.

On the basis that docking is one of the key challenges, some concepts for interfacing with existing geostationary spacecraft were investigated using multi-body dynamic simulations that included the appropriate contact dynamics of the two spacecraft interfaces. To validate the simulations, proof-of-principle testing was conducted on a tetherless air-bearing testbed to emulate zero gravity conditions in two dimensions. The results show that a Smallsat can successfully dock with current commercial spacecraft that are not equipped with special robotic interfaces and can do so under a variety of conditions.

Introduction

On-orbit servicing has been the subject of much study over the past thirty years. The idea of maintaining space assets rather than disposing of and replacing them has attracted a variety of ideas and programs. So far the concept has only found a home in the manned space program where some success can be attributed to the Hubble Space Telescope repair missions and the assembly and maintenance of the International Space Station. For various reasons, the concept has not taken hold in the commercial space market; the closest example is the use of the Shuttle for the Palapa B2 rescue mission, which can hardly be considered an economic proposition. The primary commercial space market is the communications satellite market which is typified by a launch-to-replace strategy for the deployment of spacecraft rather than a service and upgrade approach.

As in any economically driven market, the reason is primarily one of economics and risk. The launch-to-replace approach has known risks, a well-understood financing model, and well-understood technology. A service and upgrade strategy can show downstream economic benefit but, as with any new technology, has many up-front technical risks. Further, this strategy is thought to require a greater initial financial outlay, which is hardly a selling point.

Another servicing model that is considered frequently is salvage. Interest in this subject is always re-ignited shortly after any major early life failure, but the speed of response required and the difficulty of interfacing with spacecraft that have no special servicing features generally are seen as show-stoppers.

The objective of the work described in this paper was to examine both the economic and technical difficulties

posed by these current circumstances and to develop an economically viable technical baseline for servicing existing geostationary communications spacecraft. The economic constraints posed led to the development of a smallsat service vehicle concept, while the technical challenge of docking with existing spacecraft was addressed directly by designing a docking system that was validated by simulation and test.

Background

Previous Space Repairs

Early in the Space Shuttle program, the potential for on-orbit servicing was explored on missions to rescue the Palapa-B2 and Westar satellites. The best known space repair, however, is that of the Hubble Space Telescope in 1993. Astronauts operating from the Space Shuttle installed a set of corrective optics to counter the effects of Hubble's flawed primary mirror.

Aside from these shuttle-based repairs involving veteran astronauts, no repair has been conducted in space using one spacecraft to repair another. Part of the perceived difficulty is that spacecraft are constructed for assembly by human hands, not for future robotic access. One of the criticisms leveled at on-orbit servicing concepts is that the cost of developing robotic access is too high to justify its use; the robotic systems required are also seen as too complex and developmental for anything other than occasional use. In fact, little real development would be necessary because the majority of the technology required already exists and has been either used or demonstrated in space.

Existing Robotic Systems for On-Orbit Servicing

Canadarm and Canadarm2

Over the past two decades, the Shuttle Remote Manipulator System (SRMS), also known as Canadarm, has enabled on-orbit servicing missions such as payload/satellite deployment, maneuvering, servicing and retrieval, Extra-Vehicular Activity (EVA) astronaut assist, shuttle inspection and servicing, Orbit Replaceable Unit (ORU) manipulation, as well as on-orbit construction and assembly. In addition to the Palapa-B2, Westar and Hubble servicing missions, Canadarm has been involved in the International Space Station (ISS) assembly missions. Unplanned exercises for the Canadarm have included knocking a block of ice from a clogged waste-water vent that might have endangered the shuttle upon re-entry, pushing a faulty antenna into place, and successfully activating a satellite that failed to achieve its proper orbit [1].

The Space Station Remote Manipulator System (SSRMS), also known as Canadarm2, has played a key role in the assembly and maintenance of the ISS: moving equipment and supplies, supporting astronaut EVA, and servicing ORU's. Canadarm2 is capable of handling large payloads and assisting with docking the space shuttle. Figure 1 shows Canadarm2 handing off its launch cradle to the Shuttle Endeavour's Canadarm.



Figure 1. Canadarm Receiving Canadarm2's Launch Pallet

ETS-VII

Unlike the Canadarm or Canadarm2, which were built for servicing existing infrastructure in space, the ETS-VII mission was flown by NASDA as a testing ground for robotics and on-orbit servicing technologies [2]. ETS-VII was launched in 1997 and successfully conducted a series of rendezvous, docking, and space robotic technology experiments.

Some of the key experiments executed during the ETS-VII mission include:

- Visual inspection of on-board equipment by a robotic vision system
- ORU handling and simulated fuel supply experiments
- Handling of small equipment by ETS-VII small robot arm including the use of a taskboard handling tool
- Handling of truss structures
- An antenna assembly experiment
- Ground teleoperation of the ETS-VII robot
- Handling and berthing of the 410kg ETS-VII target satellite with ETS-VII robot on chaser satellite
- Rendezvous and docking by the ETS-VII chaser satellite with the ETS-VII target satellite

Emerging On-Orbit Servicing Concepts

Commercial

Orbital Recovery Corporation (ORC), an aerospace technology company based in Washington, D.C., has been developing on-orbit servicing concepts to extend the life of Geostationary Earth Orbit (GEO) communications spacecraft. ORC's concepts are intended to provide satellite stationkeeping functionality or reboost prior to on-board propellant exhaustion. In December of 2002 ORC proposed a rescue plan for the SES ASTRA-1K satellite, one of the world's largest telecommunications satellites, that was stranded in Low Earth Orbit (LEO) after its launch vehicle malfunctioned. The salvage mission would use ORC's Geosynch Spacecraft Life Extension System (SLES) to boost ASTRA-1K to the desired GEO orbit [3].

Civilian

The Experimental Servicing Satellite (ESS) is a GEO satellite servicing concept being developed by the Deutsche Zentrum für Luft- und Raumfahrt (DLR). Rendezvous, tracking, and in-plane and out-of-plane fly around inspection of the target satellite would be performed autonomously. ESS would be equipped with a manipulator-mounted capture tool that relies on real time video images, laser range finders, and force sensors to autonomously attach itself to the apogee motor of the target satellite [7].

Military

The Air Force Research Laboratory (AFRL) is funding development of the Experimental Satellite System, XSS-11. XSS-11 is envisioned to be a 100 kg (220 pound) microsatellite that will explore, demonstrate and flight-qualify microsatellite technologies. Emphasis will be placed on autonomous on-orbit operations. One of the mission goals is to demonstrate technologies needed for the National Aeronautics and Space Administration's (NASA) proposed plans to use spacecraft to collect samples of rocks and soil from Mars and return them to Earth for analysis [6].

Next Generation

The Defense Advanced Research Projects Agency (DARPA) is funding the Orbital Express Advanced Technology Demonstration Program, a program intended to develop and demonstrate autonomous techniques for on-orbit satellite servicing. An on-orbit servicing demonstration is planned for 2006 using two

satellites: an unmanned servicer vehicle, ASTRO, and a surrogate serviceable satellite known as NextSat. The system's capabilities include rendezvous and docking, free-flyer capture and berthing, satellite-to-satellite orbital replacement unit transfer, and on-orbit refueling. A key element of the demonstration will be the development of a non-proprietary satellite servicing interface standard that can be implemented by any satellite manufacturer [4][5].

Economics of Satellite Servicing

The economics associated with satellite servicing have been the subject of much study over the years. Initially the Shuttle was envisioned as a servicing vehicle of sorts, working in conjunction with the Orbital Maneuvering Vehicle and astronauts on the Space Station to perform in-space repairs. This concept has not been implemented simply because its costs far outweigh any of the potential benefits. Unfortunately, the difficulty in showing substantial economic benefit has been a common problem with most on-orbit servicing studies. Another strategy is to try to make the most of some of the intangible on-orbit servicing benefits such as the ability to upgrade systems after launch. This approach has been given a novel treatment using dynamic programming by Saleh *et al* in a series of recent publications [8].

The circumstances under which on-orbit servicing is beneficial can be easily derived from a relatively simple analysis. Given a need to deploy a constellation of satellites, what is the most effective strategy? The cost of the launch-to-replace approach over the life of the constellation can be summarized as:

$$C_1 = N \cdot \frac{L_c}{L_s} \cdot C_{satellite} \quad (1)$$

where N is the number of satellites in the constellation, L_c is the desired constellation lifetime, L_s is the lifetime of an individual satellite, and $C_{satellite}$ is the cost of development, production, and deployment of an individual satellite.

The cost of a service and maintenance approach over the same constellation life is:

$$C_2 = N \cdot C_{satellite} + C_{servicer} + N \cdot C_{spares} \cdot \left(\frac{L_c}{L_s} - 1 \right) \quad (2)$$

where $C_{servicer}$ is the cost of development, production and deployment of the servicing system, and C_{spares} is

the cost of development, production, and deployment of any required replacement space parts.

The economic case for servicing can be examined by dividing C_2 by C_1 and reducing as follows:

$$\frac{C_2}{C_1} = \frac{L_S}{L_C} \cdot \left(1 + \frac{C_{servicer}}{N \cdot C_{satellite}} \right) + \left(1 - \frac{L_S}{L_C} \right) \frac{C_{spares}}{C_{satellite}} \quad (3)$$

For servicing to be economically beneficial, this ratio must be less than 1. A ratio of $\frac{1}{2}$ might attract some interest, but larger ratios are of virtually no value. To minimize the ratio and thus maximize the economic benefit, the following must be true:

- The life of the constellation must be greater than the life of an unserviced satellite.
- The cost of the servicer system, however composed, must be less than the cost of the satellites it services.
- The cost of the spares must be as small in relation to the cost of the satellites they are intended for.

To meet the first condition in the geostationary communication satellite market given existing satellite lives of 15 years, one would probably have to consider a constellation life of 45 years. Unfortunately few businesses plan on this time scale, so obtaining buy-in is unlikely. However, equipment upgrades and refueling are strong candidates for an on-orbit servicing strategy as these are simple methods of extending capability or life.

To meet the second condition, one must design a servicer system that can repair many satellites.

To meet the third condition, the majority of the spacecraft components must be capable of meeting the constellation life, and the remaining life-limited items must be identifiable in advance of commissioning the constellation.

Meeting these three criteria simultaneously has not happened yet, although as the value of the geostationary communications satellites rises the likelihood of this occurring is increasing. For instance, the Hubble repair mission was worthwhile because the value of the asset being repaired was far greater than the high cost of the repair mission, which was executed using astronauts operating from the Space Shuttle.

For the present, it is far simpler to take the opportunistic view and to deal with existing failures, or to salvage and repair existing spacecraft. The criterion here is straightforward: the cost of the repair mission must be less than the value of the repaired spacecraft. Once again, to attract interest, the ratio between value and cost is large; ideally, the ratio that could attract financing is perhaps 5:1 or higher.

Translated into engineering terms, the conclusions are similar to the serviced constellation analysis. The servicer spacecraft must be inexpensive relative to the spacecraft it services, and the spares required must also be inexpensive, or likely a small percentage of the original cost. The ideal service is a software upgrade; the servicer spacecraft costs nothing as it is not required, and the spares are software code which can be downloaded into the existing architecture using a pre-established uplink interface. Alas, most failed spacecraft components are not massless and require both a launch and a mechanical interface to the spacecraft to be repaired.

As part of this study, existing spacecraft failures were examined to see which would meet the criteria that we have established: the spares and the servicer spacecraft that delivers the spares must represent a small fraction of the value of the failed satellite.

Satellite Failures

Over the past six years, there has been a consistent trend of launch and on-orbit failures of commercial, civil, and military satellites. Over US\$2B worth of on-orbit assets has been written-off as a result creating a wide range of opportunities for consideration as salvage targets. Table 1 provides a summary of recent spacecraft failures compiled from the Satellite News Digest database [9].

Possible Repairs

Possible repairs were considered for all the failure types in Table 1. In each case a high-level mission outline was developed to determine the requirements and feasibility of each repair. In the spirit of brainstorming, no repair was considered impossible at this point. From this evaluation, the three repair missions shown in Table 2 were selected as potential mission targets. These missions were selected because they represent the significant aspects of on-orbit servicing: refueling, replacement of a failed component, and the addition of an external service pack.

Table 1. Summary of Recent Spacecraft Failures

Type of Failure	Frequency of Failure ()	Observations
Battery failure	Boeing 601 (2), Boeing 601HP (3)	Charge controller failure Battery cell degradation
Solar array degradation / failure	Boeing 702 (6), Loral FS1300 (4), Lockheed Martin A2100 (1), Lockheed Martin A2100AX (1), Astrium Eurostar (1), Alcatel SpaceBus 3000A (1)	Degraded optical quality resulted in reduced power output Circuit failure in array Solar array drive problems
Transponder failure	Lockheed Martin A2100AX (2), Alcatel Spacebus 3000 (1), Loral FS1300 (2)	Potential power switching panel failure Steerable beam pointing failure
Spacecraft Control Processor (SCP) failure	Boeing 601 (7), Loral FS1300 (1)	Electrical shorts involving tin-plated relay switches
Momentum wheel failure	Ball Radarsat Bus (1), Loral FS1300 (1), Orbital Sciences FUSE (1)	High momentum wheel temperatures High current draw Excessive friction
Electric Power Converter (EPC) failure	Lockheed Martin A2100AX (1)	High EPC temperatures
Xenon ion propulsion system failure	Boeing 601HP (1)	Potentially blocked XIPS grid due to build-up of residue
Thruster failure	Astrium Eurostar (1), Loral FS1300 (3)	Thruster potentially leaking
Antenna failure	Boeing 601 (1)	Specific material caused performance shortfall on multiple access phased array antenna
Single event upset	Loral 7000 (1)	Possible magnetic cloud event caused massive short in circuitry
Blocked pressurant valve	Boeing 601 (1)	Blockage of valve resulted in loss of fuel tank pressure
Power amplifier failure	Boeing 601 (1)	None

Table 2. Selected Potential Repairs

Failure	Spacecraft Requirement	Repair	Comments
Spacecraft Control Processor (SCP)	System management	Replace SCP	Requires access to interior of spacecraft and to internal harness
Momentum wheel	Attitude control	Replace momentum wheel External ACS pack	Requires access to interior of spacecraft and to internal harness Mechanical interface to spacecraft, control loop closed via the ground
Fuel depleted	Orbit Maintenance and Reaction Control	Refuel External propulsion pack	Requires access to fueling valves Mechanical interface to spacecraft, control loop closed via the ground

Design Reference Mission

From these three possibilities and on the basis that the need for refueling is relatively ubiquitous, the fuel depleted case was selected as the design reference mission. Both refueling and the installation of an external propulsion pack were considered as possible approaches.

In both cases the servicer system must first rendezvous with the client spacecraft in GEO and then dock with it. The subsequent service steps then depend on the technique chosen.

In the refueling case, shown in Figure 2, the servicer system must access the client spacecraft's fuel system, transfer the propellant, and then separate from the client spacecraft to allow it to return to service. In the propulsion pack case, the servicing operation consists of deploying stationkeeping thrusters, and then returning the client spacecraft to service with the propulsion pack providing the stationkeeping function. The functions of the propulsion pack are then supervised from the ground.

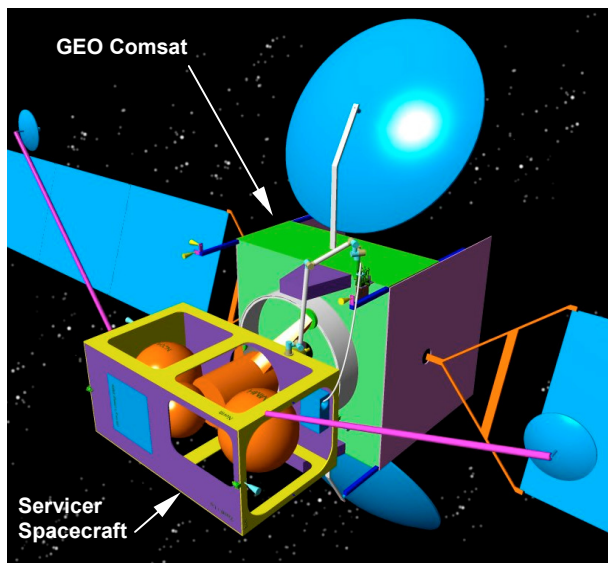


Figure 2. Servicer Spacecraft Docked to a GEO Communications Satellite

Although both approaches were developed fully, including definition of the robotic refueling tool, it was determined that the external propulsion pack mission would be functionally simpler than the refueling mission. In making this decision, the key trade is between the added required lifetime and the control of the propulsion pack versus the accessibility of the existing client satellite's fuel system. On the basis of cost and risk, a bipropellant propulsion pack was selected as the baseline approach.

Design Philosophy

The central design philosophy for the mission was to minimize cost. In keeping with this philosophy, it was decided early on that the flight segment of the servicing system should be kept as simple as possible. Servicer autonomy was dropped in favor of human-in-the-loop control wherever possible. All operational steps would be initiated and supervised by a ground-based operator. As much functionality as possible was transferred to the ground station in an attempt to keep the servicer vehicle simple, cheap, and light.

Operations Concept

Post-Insertion Orbital Maneuvers

To reach a client satellite in geostationary orbit, the servicer vehicle is first launched into a transfer orbit by a commercial booster. It must use its internal propulsion system to first roughly match the client orbit, and then perform a precision rendezvous.

The maneuvers required depend on the inclination of the transfer orbit, which is typically defined by the latitude of the launch site. Launches from Florida, Kourou, and China can reach a low inclination Geosynchronous Transfer Orbit (GTO). The steps to reach geostationary orbit are shown in Figure 3.

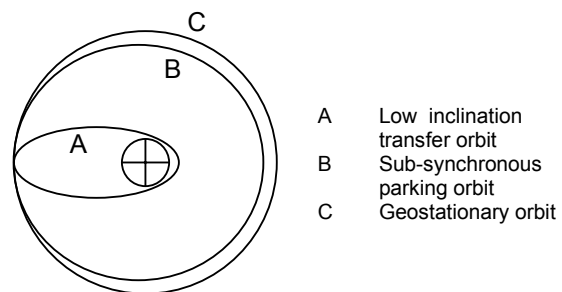


Figure 3. Low Inclination Maneuvers

The servicer performs a large burn at the apogee of its transfer orbit to place it into a slightly sub-synchronous parking orbit. It then waits, possibly for several days, until it comes to the same latitude as the client before raising its orbit to geostationary.

Launches on Russian boosters may result in high inclination transfer orbits as the launch sites tend to be quite far north. To reach geostationary orbit, a modified trajectory is required as shown in Figure 4.

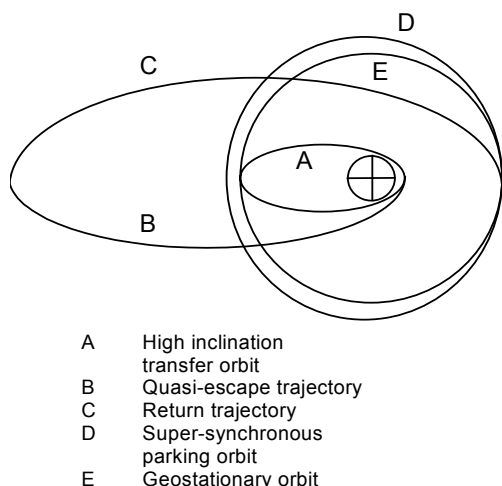


Figure 4. High Inclination Maneuvers

In this case, the servicer starts in a high inclination transfer orbit. It makes a perigee burn to place it in an almost-parabolic quasi-escape trajectory. At a large distance from the Earth, it makes another burn to remove its inclination and increase its perigee which results in the return trajectory. Once it returns to the geosynchronous altitude, a further burn places it in a slightly super-synchronous parking orbit. As before, it stays here until its latitude is the same as the client at which point it makes a final burn.

Table 3 shows the delta-V required to perform these maneuvers. Propellant tankage is shared between the payload and the propulsion system. This means that unused maneuvering margin can be employed to further extend the client satellite's life.

Table 3. Required Servicer Delta-V

Launch Inclination	Required Servicer Delta-V Including Margin
Low (28°)	2000 m/s
High (55°)	2200 m/s

The following subsections describe the baseline concept for servicer spacecraft rendezvous, proximity operations, and docking with the client satellite.

Insertion into GTO

Following insertion into GTO by the launch vehicle, coarse orbit determination is made via launch data and ground-based radar tracking of the spacecraft during near perigee motion. It may be necessary at this point to detumble the servicer satellite to within acceptable angular rates (in all axes) for proper sun sensor operation.

The initial spacecraft attitude is sensed via a coarse sun sensor comprised of six orthogonal photodiodes. An Inertial Measurement Unit (IMU) and rate gyros will be initialized from this coarse data. This coarse attitude can be used to provide an initial 3-axis stabilization for proper star tracker operation.

Fine attitude determination is sensed via a star tracker. The IMU and gyros are then reinitialized with this accurate data.

Circularization into NGE0 Servicing Orbit

The circularization of the servicer's orbit is accomplished by the apogee burn. Attitude control during the burn is effected by 22 Newton bipropellant thrusters. The IMU, corrected for drift by the star tracker, is used to provide feedback to the Guidance, Navigation and Control (GN&C) subsystem during the apogee burn.

Coarse Phasing into Client Proximity

The phase of the servicer's orbit will be synchronized with that of the client satellite in several stages. In the initial stage, the coarse phasing of the servicer orbit with the client is accomplished via the orbital elements provided by ground tracking (e.g., NORAD) and the client satellite operator's ground station data. This will bring the servicer to within 200 kilometres of the client. This phase is commonly referred to as initial rendezvous.

Raising/Lowering Client into Servicing Orbit

At the request of the servicer's ground segment, the client satellite operator commands the client satellite to raise/lower its orbit to match the orbital altitude of the servicer. No requirements are placed on the servicer during this portion of the phasing. The satellite operator will likely control this orbit via radio interferometry of the client satellite's ranging transponder.

Fine Phasing into Client Proximity

Following the insertion of the client satellite into the servicing orbit, the fine orbit phasing of the two spacecraft is accomplished via differential radio interferometry between the satellites' ranging transponders. Both of these transponders will be operated in a bi-static mode with the signal originating from the ground station. Multiple ground stations can be used to provide improved orbit determination via triangulation. This maneuver will bring the servicer to within 200 metres of the client spacecraft. This stage bridges both rendezvous and proximity operations.

Depending on its field-of-view, the star tracker may provide some additional capability for contingency operations.

Proximity Operations

Early in the rendezvous portion of the mission, the range is determined by the servicer using the ranging signal from the client satellite. Differential radio interferometry and orbital debris tracking information may also be used to plan minimum fuel approaches. The servicer may employ a directional receiver array that provides bearing to the client to provide for contingency operations.

Final Alignment

When the servicer is within 100 metres of the client, a camera and a co-located laser range finder will be used to plot the final approach. The radio transponder data will continue to provide range information in the event that the video is interrupted by off-nominal lighting events or data dropouts. This maneuver will bring the servicer to within 9 metres of the client spacecraft.

Docking and Undocking

Docking, and Undocking, will be accomplished with a suitably configured video camera (or cameras) and the laser range finder. The final portion of the docking maneuver is completed with the assistance of a boresight camera mounted in the tip of the docking mechanism. Accuracies of the optical docking system are on the order of 1 cm, 1 deg, 1 cm/sec, and 1 deg/sec.

Ground Segment Configuration

Command and Control

As discussed in the Design Philosophy section, most operations are performed in real-time under human control from the ground to reduce on-board complexity. Due to the short length of the free-flying mission, it is not feasible to build a custom ground-station. Instead, coverage will be rented from a commercial TT&C provider.

Since the initial transfer orbit is not geosynchronous, ground stations at different points on the globe are required to communicate with the spacecraft. The commercial network will provide the use of a number of 6-meter dishes. These would be linked via the Internet to a central control station at MDR's facilities.

Once the servicer satellite reaches geostationary orbit, it is continually visible from a fixed ground station at the correct longitude. Such a ground station may again be

rented from a commercial provider. It is also possible that the operating station for the client satellite might be used. For the final docking and robotic operations a minimum of a 13-meter antenna is required to receive the real-time video signal.

The spacecraft is capable of closing certain control loops locally, using its own sensors. This reduces the burden on the ground-based pilot and reduces the impact of communications latency. Instead of directly firing attitude thrusters, the pilot commands a vehicle body rate through a hand-controller or through pre-programmed burns. The spacecraft then fires thrusters as appropriate to achieve this rate. When the pilot releases the hand-controller it will immediately zero any attitude motion.

Translational maneuvers are handled in one of two ways. Large burns, such as orbit transfers, are accomplished by the pilot entering a desired delta-V value on a keyboard. The spacecraft fires its main engine until its accelerometers determine that the correct total impulse has been achieved. During the burn 3-axis stabilization is maintained using the attitude thrusters and an internal control-loop.

Smaller maneuvers in the docking process may be accomplished using position control instead. In this mode, the pilot enters a desired displacement from the present position. The spacecraft fires maneuvering thrusters to achieve a certain translational rate and then waits until the correct position is reached. At that point, a second thruster firing returns the satellite to its original velocity.

Human supervision is not required 24 hours a day, especially during the cruise portion of the mission. There is a limited autopilot-type behaviour that can be used when a pilot is not on duty. In this mode, the spacecraft maintains 3-axis stabilization, firing attitude thrusters occasionally as needed. It keeps a single face pointed towards the Earth, so it completes one pitch revolution each orbit. Engineering telemetry is collected and stored in solid-state memory for later read-out and analysis. No time-tagged command capability is anticipated.

Spacecraft Configuration

The servicer spacecraft is unique in its very high fuel fraction. Note that 70% of the satellite launch mass is composed of hypergolic liquid propellant. Much of the dry mass is taken by tanks to hold the fuel, plumbing to distribute it, and structure to support it. The remaining bus subsystems are compact, light and low-power. At its heart, this is a mini- or micro-satellite grafted on to a

massive propulsion subsystem and payload. The system mass budget is shown in Table 4.

Table 4. System Mass Budget

Component	Mass (kg)
Propulsion Subsystem	60
AOCS	5
Power	15
TT&C	12
Thermal Control	10
Service Module	90
Structure	60
System Margin (20%)	48
Dry Mass	302
Payload Propellant	200
Rendezvous Mass	502
Maneuver Propellant	500
Launch Mass	1002

The *rendezvous mass* is defined as the satellite mass at the moment that it docks with the client. At this point it has burned 500 kg of *maneuver propellant*, and 200 kg of *payload propellant* remain. It is important to realize that common tanks are used for these two functions. If the servicer docks particularly efficiently, using less maneuver propellant, then more fuel will remain for the payload. Similarly, if a contingency requires extra maneuvers there is a massive reserve available from the payload allocation.

Propulsion Subsystem

Large composite tanks hold mono-methyl-hydrazine (MMH) fuel and nitrogen-tetroxide (NTO) oxidizer. An additional tank of helium and a regulator are used to pressurize the propellant tanks. A single 472N main engine is used for the major orbit-adjustment burns. 16 22N bipropellant thrusters comprise the reaction-control system (RCS). This can apply attitude control torques in 3-axes. It can also produce translational forces in 3-axes. Complete RCS systems like this are typically seen only in the context of human spaceflight.

AOCS

The Attitude and Orbit Control Subsystem (AOCS) comprises the sensors and electronics needed to control the flight. The elements are:

- 3-axis solid-state rate sensor pack
- 3-axis accelerometer and rate-gyro IMU
- Star tracker
- Coarse sun sensor
- AOCS computer

The IMU is used during maneuvers to measure the total applied delta-V. This allows for closed-loop velocity

control. During cruise, the rate-gyro pack is used instead and the IMU is turned off. This saves power, and conserves the lifetime of the IMU's moving parts.

The star tracker provides an attitude reference during the cruise phase, allowing the thrusters to be pointed precisely for maneuvers. It may be occasionally dazzled by the Sun or Moon, in which case the attitude must be dead-reckoned using the rate sensors.

The coarse sun sensor, as alluded earlier, is used immediately after launch, and after any attitude control anomalies, to provide an initial attitude estimate. It is shut down once the star tracker has locked.

Stored momentum devices, such as reaction wheels, momentum wheels, or control moment gyros, were considered for this spacecraft but ultimately rejected. The free-flying mission lifetime is short and the RCS fuel consumed by attitude maintenance is not worth the power, cost and complexity of adding wheels. Global Positioning System (GPS) units were also considered, for orbit and for attitude determination. It was rejected on the grounds of low technological maturity at geostationary orbital altitudes.

Power

The power subsystem is complicated by the geometry of the docked configuration. Once docked, the client satellite casts a shadow over the servicer for approximately eight hours each day. A large lithium-ion battery is used to provide keep-alive power during this period. Solar arrays on the zenith, east and west faces provide power in sunlight.

TT&C

The Telemetry, Tracking and Command (TT&C) subsystem is also complicated by the docking geometry. Since the servicer docks with the zenith face of the client, its view of the Earth is blocked during the final approach. The baseline solution to this problem is to extend one or two booms out from the body of the servicer with antennas on the tips. These peek through the gap between the client's solar arrays and payload antennas and allow communication with the Earth.

Two downlink carriers are used. An S-band transmitter provides digital telemetry throughout the mission using a low-gain antenna. The data rate is such that a 6-meter dish on the ground is sufficient. An additional X-band transmitter, with a high-gain antenna, is used during docking to provide real-time video to the pilot. A larger 13-meter dish is needed to receive this signal and the transmitter is turned off when not needed to conserve power.

There is a single uplink carrier, on S-band, that supports low-rate digital commands. Along with the S-band downlink, it is also used for ranging and tracking.

Thermal Control

The thermal control subsystem is driven by the requirement to stay warm during the eight-hour shadowed period once docked. The avionics must be held above their survival temperature and all of the plumbing must be protected against freezing. This is accomplished by a combination of heaters and insulation. Fortunately, the spacecraft power consumption is low so cooling can be accomplished using only structure conduction. No heat-pipes or other sophisticated devices are required.

Simulation and Testing

The spacecraft docking operation is likely the most critical phase of any on-orbit servicing mission. Most servicing missions could not proceed without successful docking. The question that arises from our conceptual design is whether we can establish, with a high degree of certainty, that the apogee motor nozzle of a geosynchronous satellite can be used as a capture interface by the servicer spacecraft.

To answer this question, a preliminary dynamical analysis of the proposed capture interface was performed. Following this, a software simulation was developed to provide an in-depth understanding of the contact dynamics of two spacecraft docking. To validate the contact dynamics model, and based upon the initial analysis, a hardware testbed was developed that used scaled spacecraft mockups with representative interfaces, masses, and inertias. A layout of the testbed is shown in Figure 5.

Methodology

The simulation must address two key questions related to the behaviour of the vehicles during docking. Firstly, does the simulation accurately represent the spacecraft dynamics and docking interface contact dynamics? Secondly, does the simulation correctly predict whether or not a given interaction will result in a successful capture?

For the full 6 degree-of-freedom (DOF) simulator, the first question and the second question are closely tied together. However, it is difficult to adequately simulate two free-floating bodies, each with 6 degrees of freedom, with a ground testbed. In designing a representative hardware test, each of these questions must be addressed separately.

The docking interface consists of a Liquid Apogee Motor (LAM) on the client spacecraft and a docking probe on the servicer spacecraft. Both sides of this interface are axi-symmetric which suggests a way to reduce the degrees of freedom of the hardware simulation and still maintain similarity with the flight configuration. Given that the servicer vehicle will have a small angular misalignment relative to the client spacecraft just prior to contact, the motion of the servicer at contact can be shown to act in a plane. Since the interface is axi-symmetric, we can design a hardware simulation that confines the motion of the two vehicles to that plane of action. To ensure that we have *sufficient* (but not *necessary*) conditions to ensure successful capture, we must also design the two vehicles for the worst-case plane of action. This worst case occurs when the vehicles respond the most vigorously during the application of the contact forces. This case corresponds to the minimum moment of inertia around the nominal docking axis.

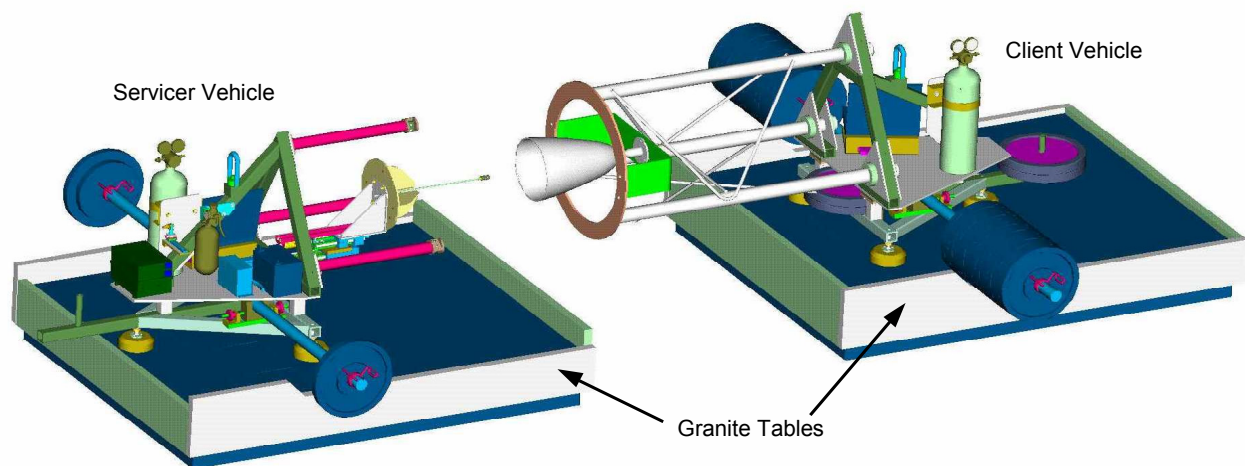


Figure 5. Docking Testbed Layout

This establishes that the worst-case capture conditions can be simulated with a planar hardware testbed. An additional difficulty, though, is that the client spacecraft has mass of 1500 kilograms which complicates the apparatus substantially. To circumvent this foreseen difficulty, a dimensionless analysis of the capture condition was conducted to determine the criteria for scaling the apparatus. The results of this analysis indicated that, for dynamic similarity, the ratio of the masses of the two vehicles and the ratio of the moments of inertia of the two vehicles must be kept 1:1 with the ratios of the actual flight values.

This scaling was further complicated by a decision to use a full-scale docking mechanism and LAM nozzle in the test. This decision mandated another scaling constraint: the distance from the nozzle to the client's centre-of-gravity must be full scale. Similarly, the distance from the docking mechanism to the servicer's centre-of-gravity must also be full scale.

A version of the full 6 DOF software dynamics simulation was created in which the planar constraints were added in order to correctly simulate the hardware testbed. It is this version of the simulation that permits a validation against the hardware; it is then possible to extrapolate the validation to the 6 DOF case.

Figure 6 shows the simulation and testing methodology that was used.

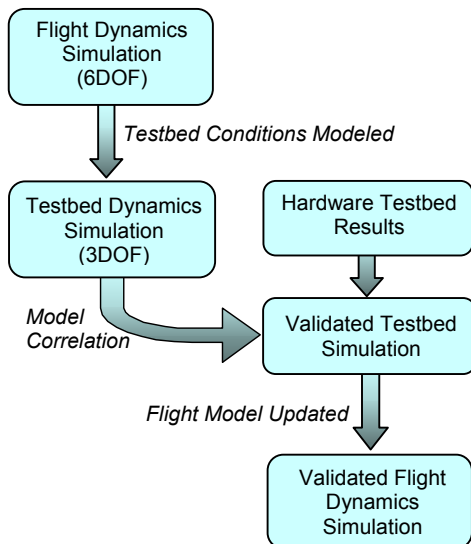


Figure 6. Docking Dynamics Simulation and Testing Methodology

Docking Validation Testbed

Test Setup

The docking testbed consisted of a servicer spacecraft mockup and a client spacecraft mockup floating on a granite surface. Precision air-bearings were used to support each vehicle to simulate zero-gee motion in the plane of the table. This provided each vehicle with low-friction in 3 degrees of freedom: x, y, and yaw.

The testbed was designed to keep the simulation dynamically similar to the design case so that capture/failure cases could be evaluated, not just velocity and loads. Trailing electrical cables and air tubes were avoided to prevent drag on each vehicle from effecting the tests. Instead, on-board nitrogen tanks were used to deliver air to the air bearings. A wireless network was implemented to transfer telemetry from the vehicles to the workstation and to transmit commands from the operator workstation to the vehicles.

Figure 7 shows the major components of the client vehicle. A full-scale mockup of the LAM nozzle was built as the docking interface. The geometry was based on typical apogee motors used onboard GEO communications satellites. It is not known how frictionally representative the anodized aluminum finish of the nozzle mockup is to a post-fired flight nozzle made of niobium with hafnium-oxide coating. However, results from the contact dynamics modeling show a relative insensitivity of the results to credible variations in the probe/nozzle contact friction.

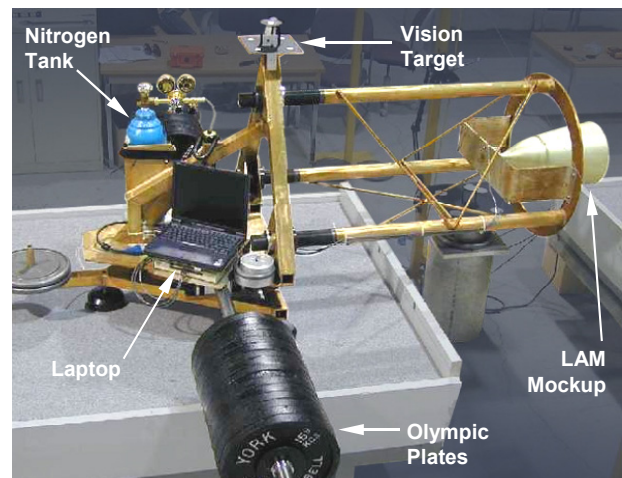


Figure 7. Client Spacecraft Mockup

Figure 8 shows the major components of the servicer vehicle. A prototype docking mechanism was mounted forward of the vehicle consisting of a probe, a compliance mechanism, and a berthing drive unit. The probe consists of two spring-loaded fingers mounted at the end of a flexible shaft. The shaft was mounted to a compliance mechanism consisting of a linear guide and extension spring. The compliance mechanism was mounted to a berthing drive consisting of a ball-screw actuated slide.

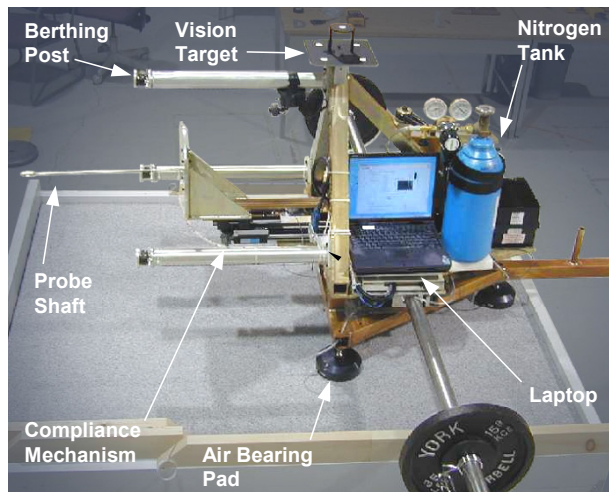


Figure 8. Servicer Spacecraft Mockup

Each vehicle was built on a custom aluminum frame with a platform used to support laptops and gas handling equipment. Olympic-grade weight plates mounted on a 2" solid steel bar were used to adjust the mass, inertia, and centre-of-gravity of each vehicle.

Photogrammetry was used to measure the relative position and orientation of the servicer and client vehicles during a given test. A vision system obtained image data from two overhead cameras. Each camera tracked a centroid pattern of visual targets mounted on each vehicle.

Each vehicle was instrumented with strain gauges and load cells to measure the forces and moments generated during the docking trials. Four major physical parameters can be manipulated by the design engineer: axial stiffness, lateral stiffness, axial damping, and lateral damping.

The axial stiffness of the docking mechanism was measured by applying a known force to the compliance mechanism then measuring the spring displacement. Axial damping was calculated by manually exciting the compliance mechanism then measuring the axial load cell response. Lateral probe stiffness and damping was calculated by manually exciting the probe shaft then measuring the shaft strain gauge response.

The interface friction coefficient between the nozzle and the probe tip can also be affected during the design, but sensitivity analyses show that the other parameters dominate the dynamical behavior. The measured parameters and empirical test data for the friction coefficient were incorporated into the contact dynamics model to correctly simulate the hardware testbed.

Test Sequence

Before performing a docking test, the misalignment conditions for each vehicle were set. Each vehicle used a multi-beam laser level to project three beams onto bumpers installed around the perimeter of each table. Rulers were mounted on the bumpers to measure beam positions. A unique set of beam positions exists for any given combination of x, y, and yaw misalignments. The position and orientation of each vehicle was adjusted until the projected beam positions indicated that the desired misalignment was reached.

The servicer vehicle was accelerated toward the client using an on-board compressed air thruster. The system consisted of a high-pressure air tank that delivered approximately 100 psi to a nozzle located near the rear of the servicer. The approach velocity of the servicer was controlled by the duration of the thruster firing and measured by the photogrammetric vision system throughout its trajectory.

Figure 9 shows the servicer vehicle during its final approach. For a typical test, the servicer drifted freely toward the client until the probe head made contact with the LAM. After the initial contact, there was typically sliding/bouncing contact between the probe head and the nozzle surface until the probe enters the throat of the nozzle. The spring-loaded probe head fingers retract to clear the throat then spring open once clear. This provides capture retention of the client vehicle.

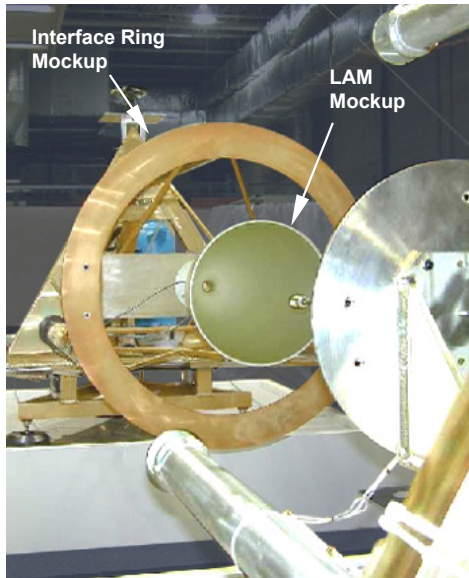


Figure 9. View From Servicer Mockup During Final Approach

Once soft-dock was established, the berthing drive was commanded to retract the probe until the berthing posts on the servicer contact a mockup of the launch vehicle interface ring on the client. The berthing drive can be adjusted to achieve the desired preload at the servicer/client interface.

Contact Dynamics Validation

The 3 DOF contact dynamics model was correlated against test data gathered from the docking testbed. A number of tests were performed at different approach speeds and misalignments to generate sufficient data for model correlation. A few severely misaligned cases were performed to determine if the validated model could correctly predict the behavior of a failed docking attempt.

The following system parameters were taken into consideration for model validation:

- Mass and inertia of each vehicle
- Position and orientation of each vehicle
- Relative linear and angular velocity
- Contact geometry
- Contact friction and stiction
- Compliance and damping of the system

Parameters such as mass, inertia and geometry were measured directly. Position, orientation, linear velocity and angular velocity were calculated by the vision system for each run. Contact forces and moments were measured using the strain gauges and loadcells. Contact stiffness, contact friction and damping coefficients were

identified using an optimization technique based on genetic algorithms, which are a form of evolutionary computation.

After the contact dynamics model was correlated, predictions from the simulator were compared against testbed results. The simulator always correctly predicted if a docking attempt was successful or unsuccessful. Prediction error increased slightly for very large initial misalignments.

An in-depth understanding of docking dynamics has been gained through simulation and testing. The validated contact dynamics model can be used with confidence to generate 6 DOF flight predictions. Although the hardware and software simulators were developed for a particular docking scenario, they can be easily modified to simulate docking dynamics for any on-orbit servicing opportunity. The combination of simulation and testing clearly shows that docking with existing GEO communications satellites is possible.

Ground Segment Emulator

A ground segment emulator, shown in Figure 10, was developed to simulate man-in-the-loop operations during the critical rendezvous phase of the mission. A graphical user interface served as a control console and provided camera views of the client satellite. Keyboard input and/or hand controller commands were used to maneuver the servicer vehicle into the client spacecraft capture envelope.

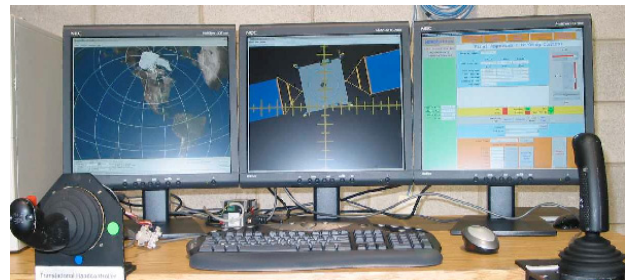


Figure 10. Ground Segment Emulator

The three screens in the Ground Segment Emulator provided the operator with (center monitor) simulated camera views from the servicer cameras, (right monitor) telemetry, command, and control data, and (left monitor) ground track data to assist with situational awareness during post-injection, orbit raising, and coarse phasing operations.

Simulated Flight Camera Views

A boresight camera located at the tip of the docking probe provided an excellent view of the docking approach, shown in Figure 11. The reticle in this view

was in a cross-pattern, showing lateral and vertical position, relative vehicular yaw, and velocity offsets of the servicer relative to the client.

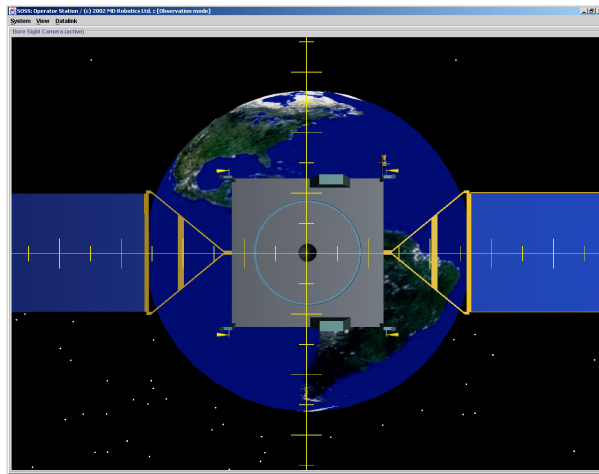


Figure 11. Boresight View From Simulation

Cues for relative vehicular pitch and roll were available in the relative motion of the nozzle opening with respect to the launch adapter ring. This provided an independent means of verifying the relative attitude between the two earth-pointing spacecraft. The operator used the crosshair of the reticle to aim the servicer towards the client vehicle's apogee motor nozzle.

Rendezvous Simulation Results

A set of rendezvous, proximity operations, and docking procedures were set down by the mission designers for use by the servicing spacecraft operators. These procedures, although refined during subsequent operational simulations, proved able to guarantee successful and timely rendezvous with the client spacecraft. Repeated simulations (with the full suite of rendezvous sensors specified for the mission) showed that a trained operator could reliably achieve rendezvous under the expected sensor uncertainties and within the designed rendezvous propellant margins.

Docking Simulation Results

During the course of development, it became apparent that the use of hand controllers to remotely pilot the servicer, although possible, was not the favored approach. The preferred approach, due to the latency in command, visualization, and control, was to use keyboard commands to "jog" the vehicle into position by use of preset burns and counterburns. Most operators were able to perform a successful docking immediately after being briefed on the use of this procedure, whereas

using the hand controllers often required many training runs to reach the same level of success.

The ground segment emulator served as a valuable platform to develop and test rendezvous techniques. Feedback from operators was used to develop the lowest risk, easiest-to-fly rendezvous strategy. Like the docking simulator, the ground segment emulator can be easily modified to simulate rendezvous and docking operations for any on-orbit servicing opportunity.

Future Work

Currently, the work described in this paper is being extended to low earth orbit where communications are more difficult and the orbital effects are more exaggerated. The scenario being closely considered is that of Radarsat-1, a Canadian remote sensing satellite that has provided useful information to both commercial and scientific users in the fields of agriculture, cartography, hydrology, forestry, oceanography, ice studies, coastal monitoring, and disaster management. Recently, however, several failures have occurred in the spacecraft's attitude control system. Both prime and back-up pitch momentum wheels, used to maintain the spacecraft's gyroscopic stiffness, have failed. In addition, problems have developed with the spacecraft's horizon scanners used for attitude sensing. These components are necessary to ensure the three-axis attitude control required for precise pointing of the spacecraft.

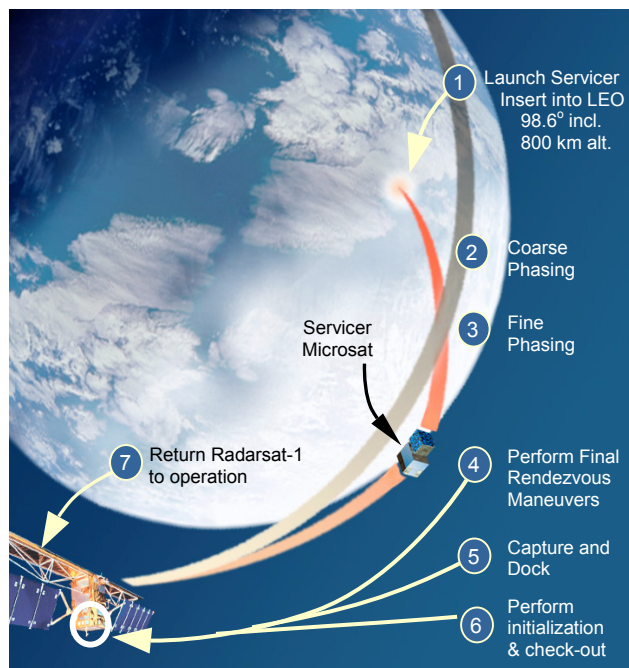


Figure 12. Radarsat-1 Repair Mission Concept

While there are workarounds currently in place, an on-orbit servicing approach to solve Radarsat-1's attitude control system problems is worth investigating. The mission concept being examined is based on the use of a microsat (less than 100 kg) to deliver an attitude control pack to Radarsat-1 as shown in Figure 12.

The proposed mission embodies concepts such as autonomous maneuvering in LEO, out-of-plane rendezvous, and satellite docking with an unprepared interface.

Conclusion

This paper demonstrates that servicing existing spacecraft with a smallsat is viable with present technologies. A smallsat is the ideal vehicle for these operations particularly for salvage-oriented missions in which the mission must be low-cost and the required repair function is known in advance.

Two key technical risks have been substantially mitigated during the course of this study. End-to-end rendezvous analysis has demonstrated that the conditions for satellite capture can be reliably achieved in GEO. Secondly, given these capture conditions, it has been shown that docking with existing spacecraft is entirely possible.

References

1. King, D., "Space Servicing: Past, Present and Future." Proceedings of the 6th i-SAIRAS Symposium, Montreal, Canada, June 2001.
2. Ohkami, Y. and M. Oda, "NASDA's Activities in Space Robotics." Proceedings of the 5th i-SAIRAS Symposium, Noordwijk, The Netherlands, June 1999.
3. Orbital Recovery Corporation Press Release (www.orbitalrecovery.com/news.html)
4. SpaceDaily News Article (<http://www.spacedaily.com/news/robot-02g.html>)
5. Defense Advanced Research Projects Agency Press Release (www.darpa.mil/body/news.html)
6. Lockheed Martin Press Release (www.spaceflightnow.com/news/n0108/26xss11/)

7. Settelmeier, E., E. Lehl, W. Oesterlin, R. Hartmann, K. Landzettel, "The Experimental Servicing Satellite ESS." Proceedings of the 21st ISTS Symposium, Omiya, Japan, 1998.
8. Saleh, J.H., E.S. Lamassoure, D.E. Hastings, D.J. Newman, "Flexibility and the Value of On-Orbit Servicing: A New Customer-centric Perspective", Proceedings of the 2001 Core Technologies for Space Systems Conference, Colorado Springs, CO, November 2001.
9. Satellite News Digest – Outages and Failures Database (www.sat-index.com/failures)